

# Testing Fundamental Particle Physics with the Galactic White Dwarf Luminosity Function

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**Abstract.** Recent determinations of the white dwarf luminosity function (WDLF) from very large surveys have extended our knowledge of the WDLF to very high luminosities. It has been shown that the shape of the luminosity function of white dwarfs (WDLF) is a powerful tool to test the possible properties and existence of fundamental weakly interacting subelectronvolt particles. This, together with the availability of new full evolutionary white dwarf models that are reliable at high luminosities, have opened the possibility of testing particle emission in the core of very hot white dwarfs. We use the available WDLFs from the Sloan Digital Sky Survey and the SuperCOSMOS Sky Survey to constrain the values of the neutrino magnetic dipole moment ( $\mu_\nu$ ) and the axion-electron coupling constant ( $g_{ae}$ ) of DFSZ-axions.

## 1. Introduction

Astrophysical arguments can provide powerful constraints to the properties of elementary particles. This is particularly true at the subelectronvolt scale (Jaekel & Ringwald 2010). Weakly interacting subelectronvolt particles can be abundantly created in the hot and dense stellar plasmas and then escape from the stellar interior without further interactions (see Raffelt 1996 for a detailed review). Consequently, if they exist, these particles provide a local energy sink for the stellar structure. This alters the structural and evolutionary properties predicted for different stars. The observable impact of these changes provide some of the most powerful limits on the properties of real or hypothetical subelectronvolt particles like neutrinos and axions (Viaux et al. 2013). In particular, white dwarf cooling is sensitive to the hypothetical exis-

tence of DFSZ-axions<sup>1</sup> or a magnetic dipole moment of the neutrino ( $\mu_\nu$ ). This allows using white dwarfs to constrain the values of the axion-electron coupling constant ( $g_{ae} = 2.8 \times 10^{-14} \times m_a^{\text{meV}} \cos^2 \beta$ , where  $m_a$  is the mass of the axion) and  $\mu_\nu$  (Blinnikov & Dunina-Barkovskaya 1994). In the context of the strong CP problem, Isern et al. (2008) have shown that modern white dwarf luminosity functions (WDLF), coming from large sky surveys, offer a new possibility to learn about elementary particle physics. Here we study the constraints that can be derived for  $\mu_\nu$  and  $g_{ae}$  from the use of recent determinations of the WDLF and the aid of state-of-the-art white dwarf models.

## 2. The white dwarf luminosity function

To construct the theoretical WDLFs to be compared with the derivations of the WDLF of the Galactic disk we use the method described by Iben & Laughlin (1989). In this approach the number of white dwarfs per logarithmic luminosity and volume is computed as

$$\frac{dn}{dl} = - \int_{M_1}^{M_2} \psi(t) \left( \frac{dN}{dM} \right) \left( \frac{\partial t_c}{\partial l} \right)_m dM \quad (1)$$

where  $\psi(t)$  is the galactic stellar formation rate at time  $t$ ,  $N(M)$  is the initial mass function and  $t_c(l, m)$  is the time since the formation of a white dwarf, of mass  $m$ , for the star to reach a luminosity  $\log(L/L_\odot) = l$ . In order to compute the integral in equation 1 we also need the initial-final mass relation  $m(M)$ , and the pre-white dwarf stellar lifetime  $t_{ev}(M)$ . We adopt a Salpeter initial mass function, the  $m(M)$  relation from Salaris et al. (2009) and the  $t_{ev}(M)$  from the BaSTI database<sup>2</sup>. It is worth noting that, for a given white dwarf luminosity ( $l$ ) and mass of the progenitor ( $M$ ) the formation time of the star,  $t$ , is obtained by solving  $t + t_{ev}(M) + t_c(l, m) = T_{OS}$ , where  $T_{OS}$  is the assumed age of the oldest star in the computed population. The lowest initial mass that produces a white dwarf with luminosity  $l$  at the present time ( $M_1$ ) is obtained from  $t_{ev}(M) + t_c(l, m) = T_{OS}$ . The value of  $M_2$  corresponds to the largest stellar mass progenitor that produces a white dwarf. In what follows the value of  $\psi(t)$  is assumed constant and its value is obtained from normalization to the observational WDLF.

In order to compute theoretical WDLFs that take advantage of new available data that extends to the high luminosity regime, full evolutionary models derived from the progenitor history are to be preferred. The initial white dwarf models adopted in our simulations were taken from Renedo et al. (2010). Then we computed the values of  $t_c(l, m)$  under the assumption of different axion masses and values of the magnetic dipole moment of the neutrino by using LPCODE stellar evolution code. This was performed by including self-consistently the anomalous energy losses in the computation of the cooling sequences. See Miller Bertolami (2014) and Miller Bertolami et al. (2014) for details. Sequences were computed for axion masses of  $m_a \cos^2 \beta = 2.5, 5, 7.5, 10, 15, 20$  &  $30$  meV and neutrino magnetic dipole moments of  $\mu_{12} = 1, 2, 5$  and  $10$ , where  $\mu_{12} = \mu_\nu / (10^{-12} e\hbar / (2m_e c))$ , as well as for the standard case ( $\mu_{12} = m_a = 0$ ).

<sup>1</sup>DFSZ-axion models (after Dine et al. 1981; Zhitnitsky 1980) allow for the coupling of axions to leptons.

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### 3. Discussion and conclusions

As shown by Miller Bertolami (2014) different modern WDLFs do not agree with each other within their own quoted error bars. Then, a conservative estimation of the WDLF of the Galactic disk and its uncertainties can be done by taking two completely independent derivations of the WDLF and estimating the differences between both (see Miller Bertolami 2014 for details). In Fig. 1 we compare the theoretical WDLFs with the WDLF of the Galactic disk constructed in this way. It is worth noting that, in agreement with Isern et al. (2008), the upper panel of Fig. 1 shows that in the case of axions the best fit is obtained for DFSZ-axions masses of  $\sim 5\text{meV}$ . While this result is only marginally significant from a statistical perspective (see inset) it is interesting in the light of the forthcoming International Axion Observatory (IAXO) which will be able to explore axion masses in the range  $m_a \cos^2 \beta \gtrsim 3\text{ meV}$ . As shown in the insets of Fig. 1, a  $\chi^2$ -test indicates that WDLFs constructed with values of  $g_{ae} \gtrsim 2.3 \times 10^{-13}$  and  $\mu_\nu \gtrsim 5 \times 10^{12} e\hbar/(2m_{ec})$  are at variance with the WDLF of the Galactic disk at the  $2\sigma$ -level. These values are close to the best available constraints coming from the study of globular clusters (Viaux et al. 2013). While this shows that modern WDLFs are an excellent tool for constraining the properties of axions and neutrinos these constraints should not be taken at face value. First, theoretical uncertainties in the theoretical cooling times might be as high as  $\sim 10\%$  in some regimes (Salaris et al. 2010). Second, departures from the constant stellar formation rate, as those inferred by Rowell (2013), might also introduce uncertainties of the order of  $\sim 10\%$  in the computed values. When taken into account, these two effects should slightly weaken the previous constraints. Even more, discrepancies between different WDLFs suggest there might be some relevant unaccounted systematic errors. A larger set of completely independent WDLFs, as well as more detailed studies of the theoretical WDLFs, and their own uncertainties, is desirable to explore the systematic uncertainties behind these constraints.

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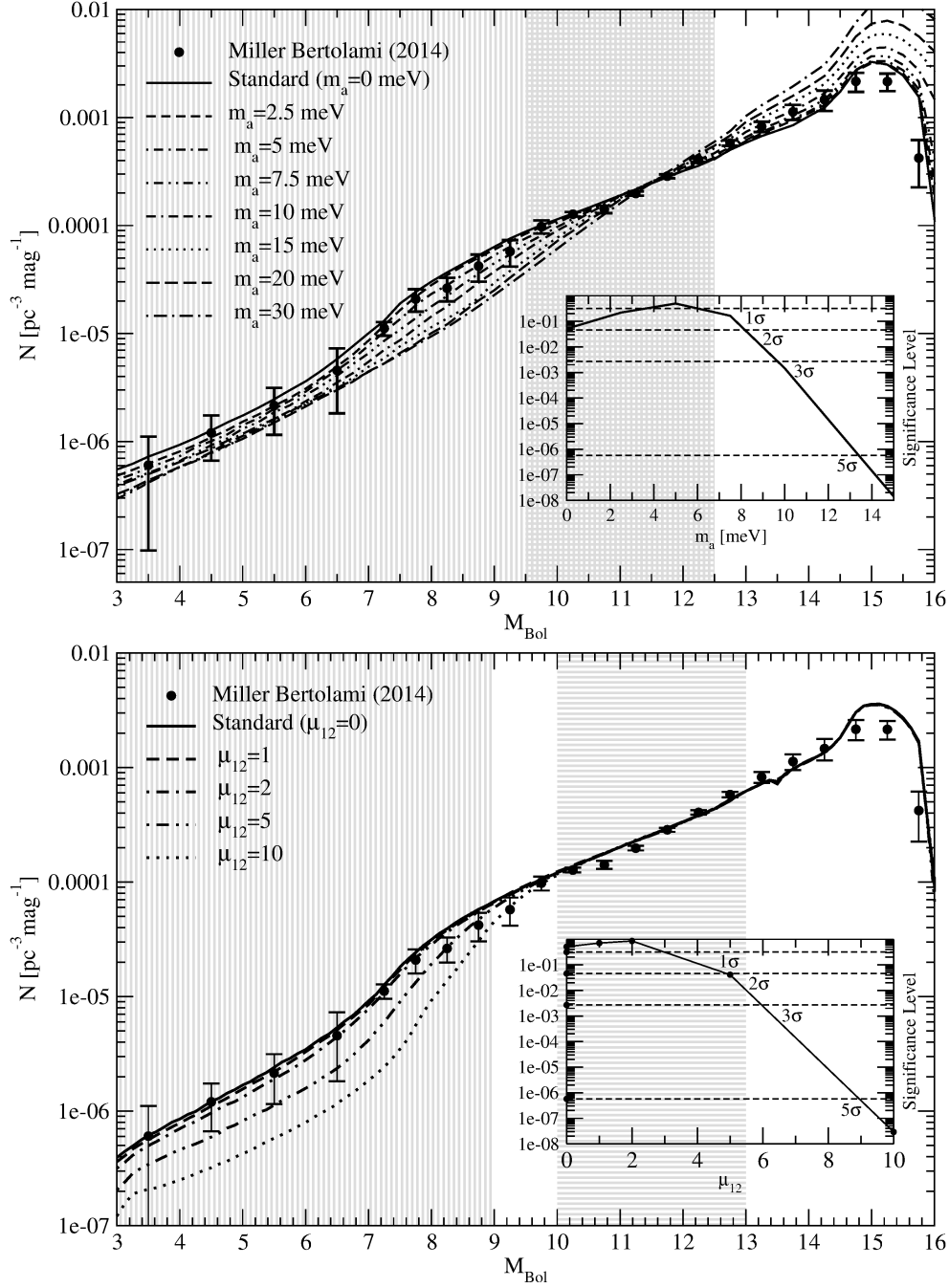


Figure 1. *Upper Panel:* Comparison of the WDLF estimated by Miller Bertolami (2014) (from the independent WDLFs of Harris et al. 2006, Krzesinski et al. 2009 and Rowell & Hambly 2011) with the theoretical WDLFs computed under the assumption of different masses for the DFSZ-axion. Vertical grey lines indicate the range adopted for the comparison in the  $\chi^2$ -test, while horizontal grey lines indicate the range of luminosities adopted for the normalization of the theoretical WDLFs. *Lower Panel:* Same as the upper panel but for the theoretical WDLFs derived under different assumptions for the value of the magnetic dipole moment of the neutrino. Insets show the significance levels for  $\chi^2$ -test between the observationally derived WDLF and the WDLFs computed under different anomalous energy losses.